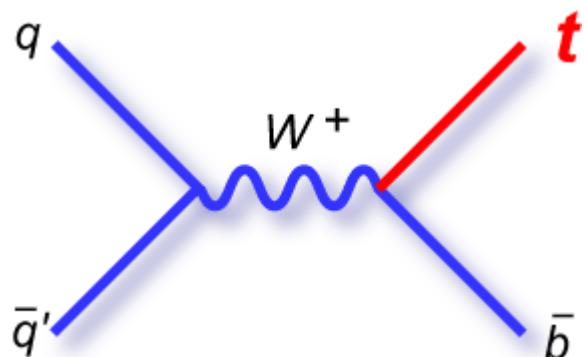


Evidence for single top production at the Tevatron

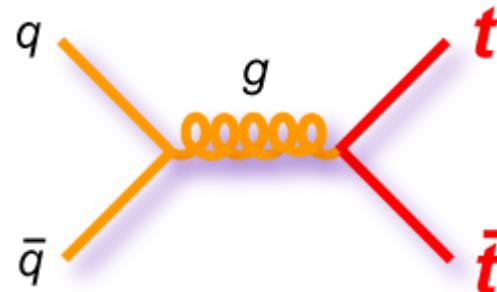


Supriya Jain
University of Oklahoma
on behalf of D0 and CDF
collaborations

Rencontres de Moriond QCD 2008
11 March 2008

Production of top quarks at the Tevatron

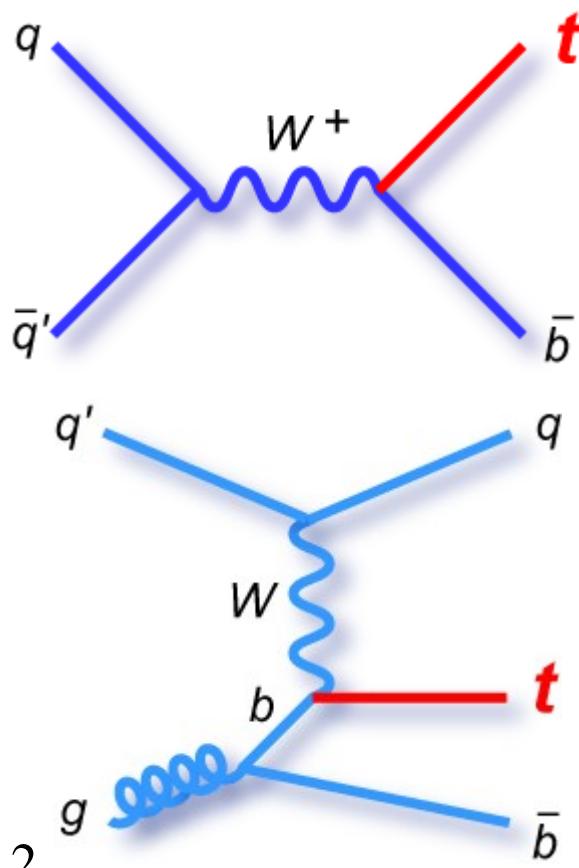
- Strong interaction



$$\sigma_{\text{ttbar}} = 6.77 \pm 0.42 \text{ pb}$$

- Distinct event signature from the decay of a massive object

- Electroweak interaction



$$\sigma_{\text{s-channel}} = 0.88 \pm 0.14 \text{ pb}$$

$$\sigma_{\text{t-channel}} = 1.98 \pm 0.30 \text{ pb}$$

Signal : Background $\sim 3 : 1$

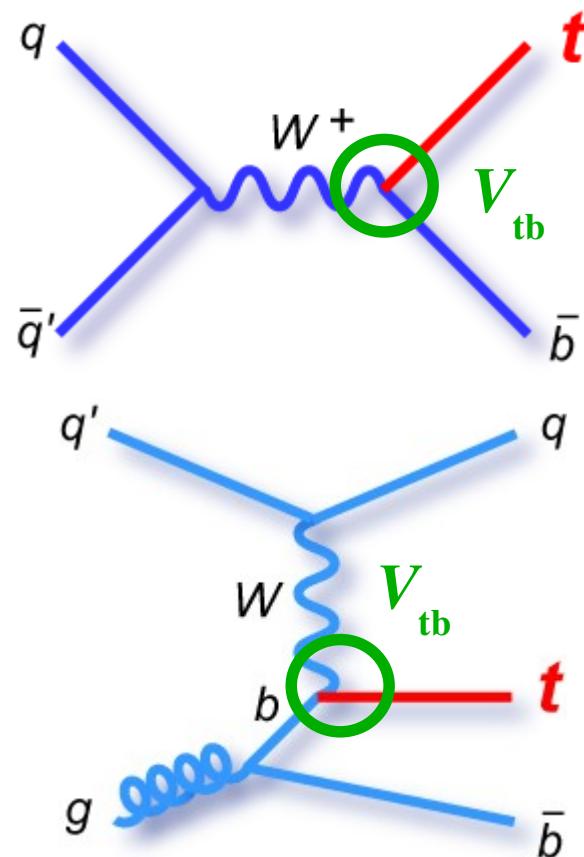
- Smaller cross sections
- One less massive object hence difficult to identify

Signal : Background $\sim 1 : 15$

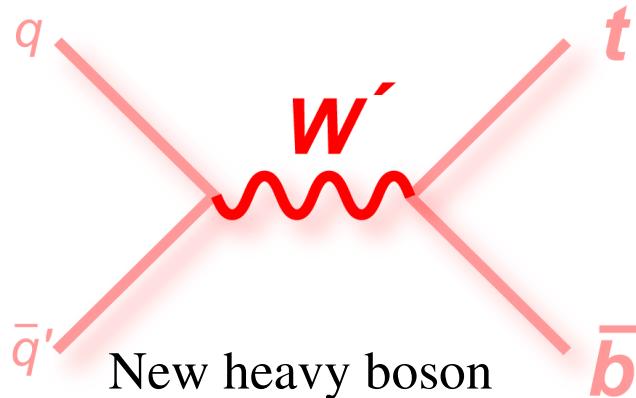
Quoted cross sections at $M_{\text{top}} = 175 \text{ GeV}$

--- N. Kidonakis, R. Vogt, Phys. Rev. D **68** 114014 (2003);
Z. Sullivan, Phys. Rev. D **70**, 114012 (2004)

Single top production: Goals



- Claim discovery of single top production
- Measure production cross sections
 - $\sigma_s, \sigma_t, \sigma_{s+t}$
- Perform direct measurement of CKM matrix element $|V_{tb}|$
- Study top quark polarization
- Establish techniques useful for searches for small signals, like the Higgs search
- Probe new physics effects



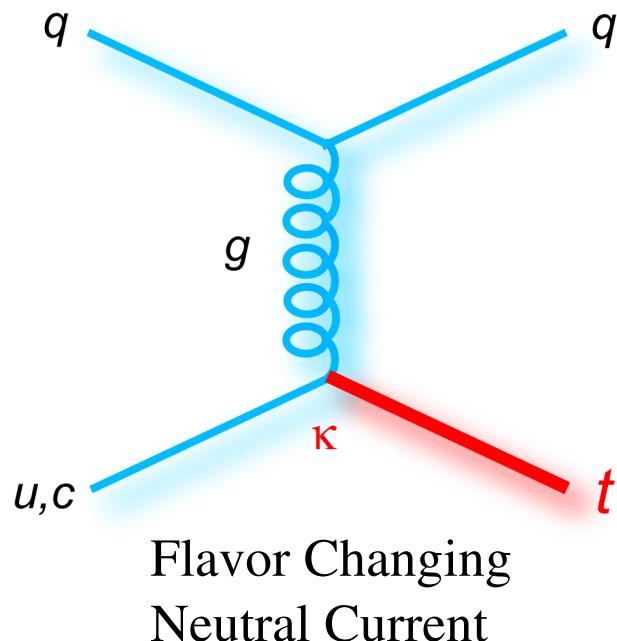
- Recent results

- Limits on W' from CDF

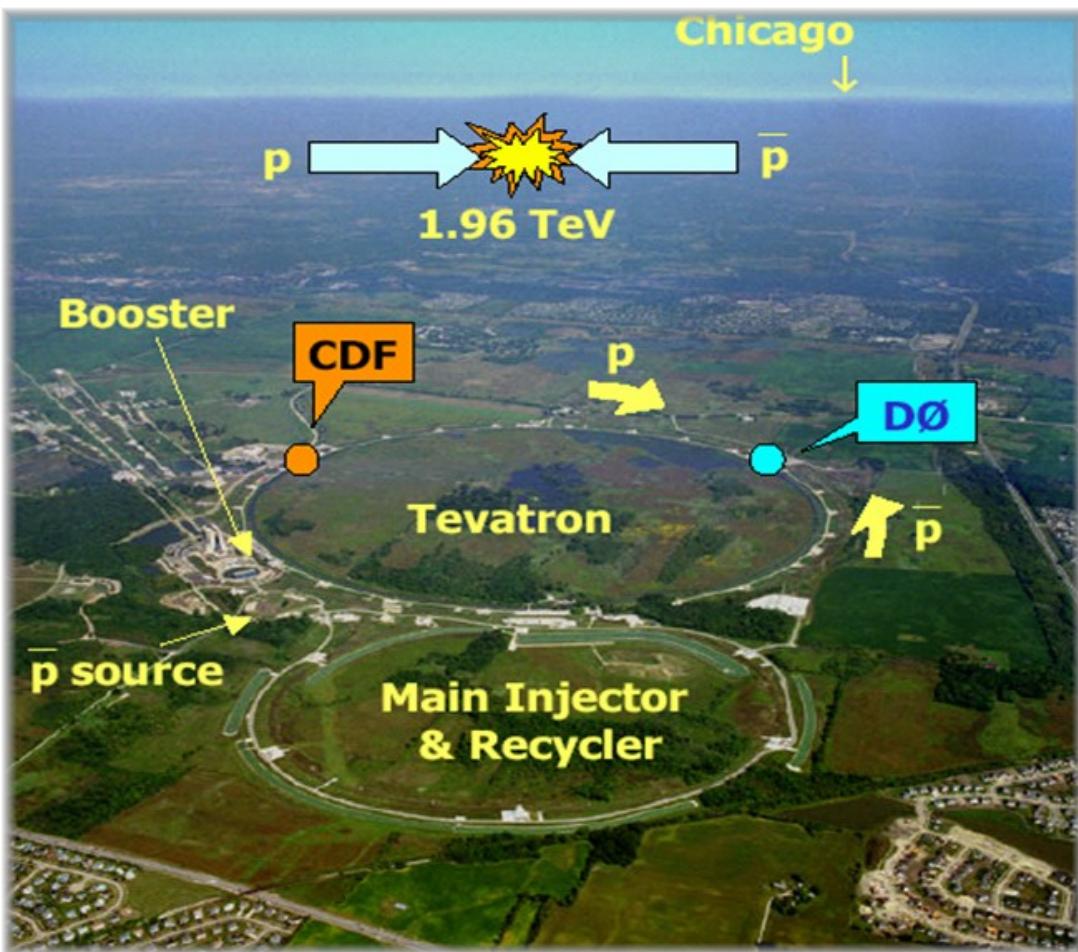
- $M(W') > 800 \text{ GeV to } 825 \text{ GeV,}$
depending on couplings and decays

[D0: PLB 641:423-431 (2006)]

- FCNC gluon coupling limits from D0
 - [PRL 99:191802 (2007)]
 - $\kappa^c/\Lambda < 0.15 \text{ TeV}^{-1}$ and $\kappa^u/\Lambda < 0.038 \text{ TeV}^{-1}$
(Λ is the new physics scale)



Evidence for single top production at Tevatron

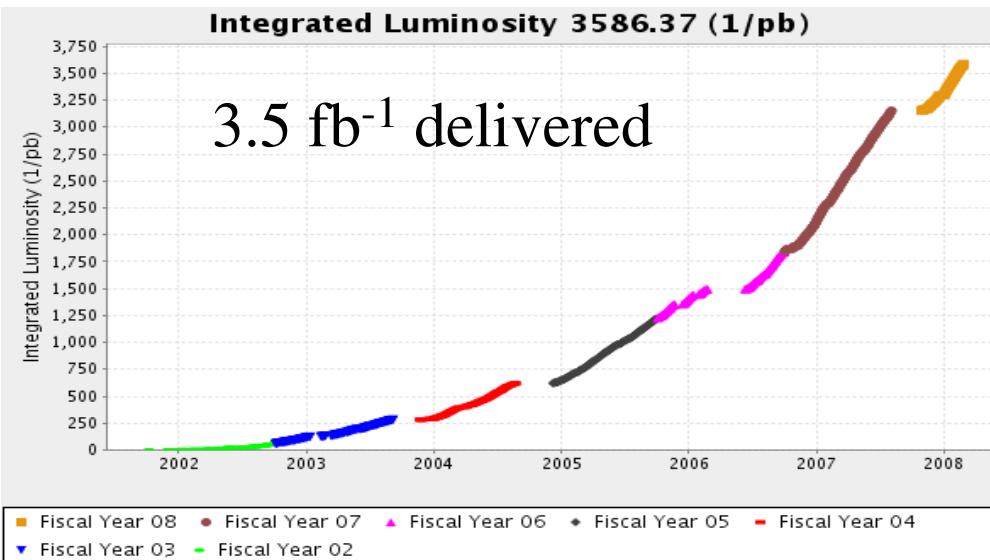


DØ

- First evidence at 3.4σ using 0.9 fb^{-1} data [PRL 98, 181802 (2007)]
- Improved two of its three analyses (Bayesian NN, and Matrix Element) [arXiv.org:0803.0739, submitted to PRD]

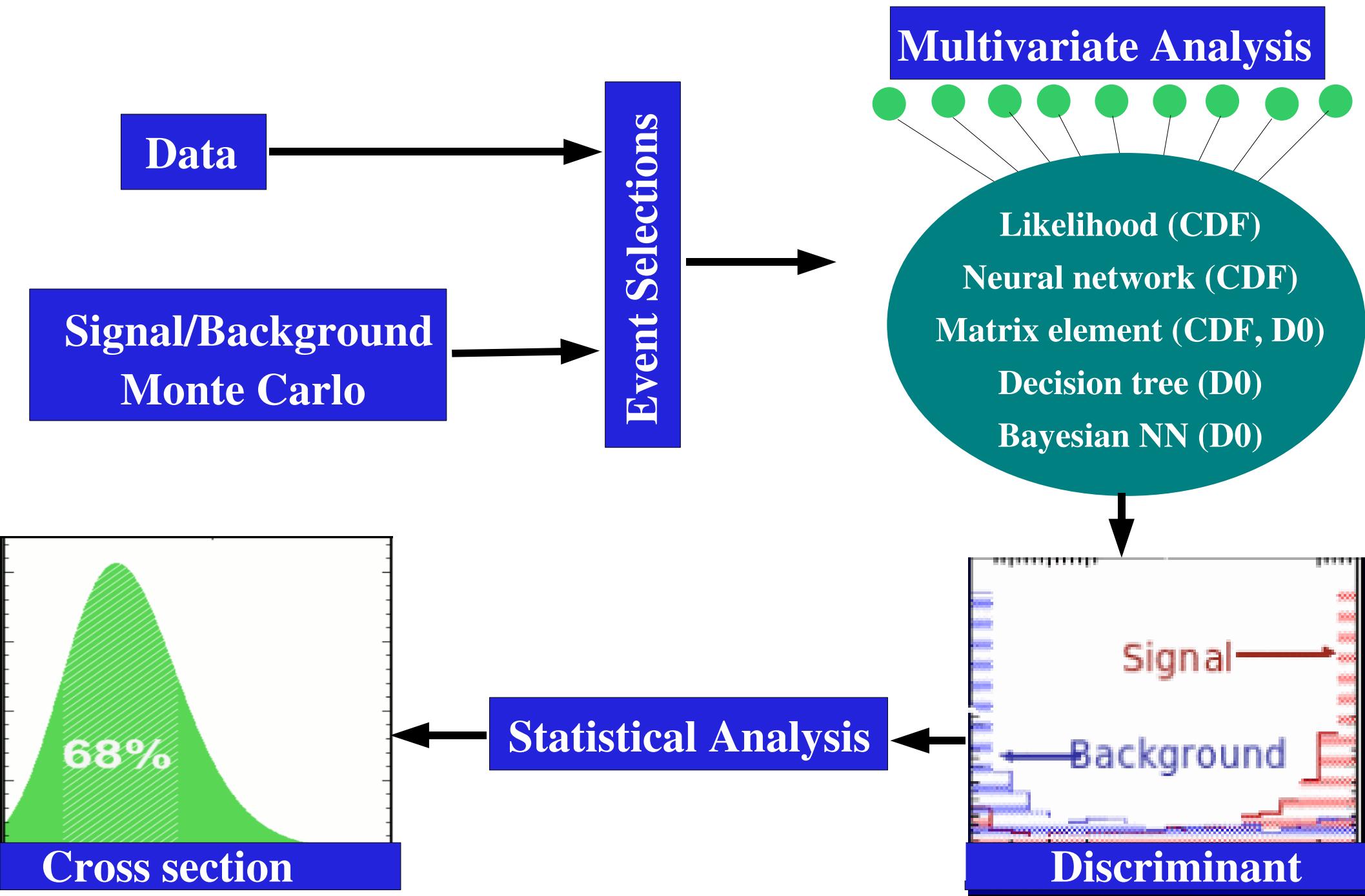
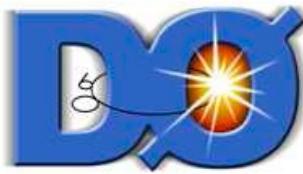
CDF:

- Also saw evidence at 3.1σ (using 1.5 fb^{-1} data)
- Latest results using 2.2 fb^{-1}

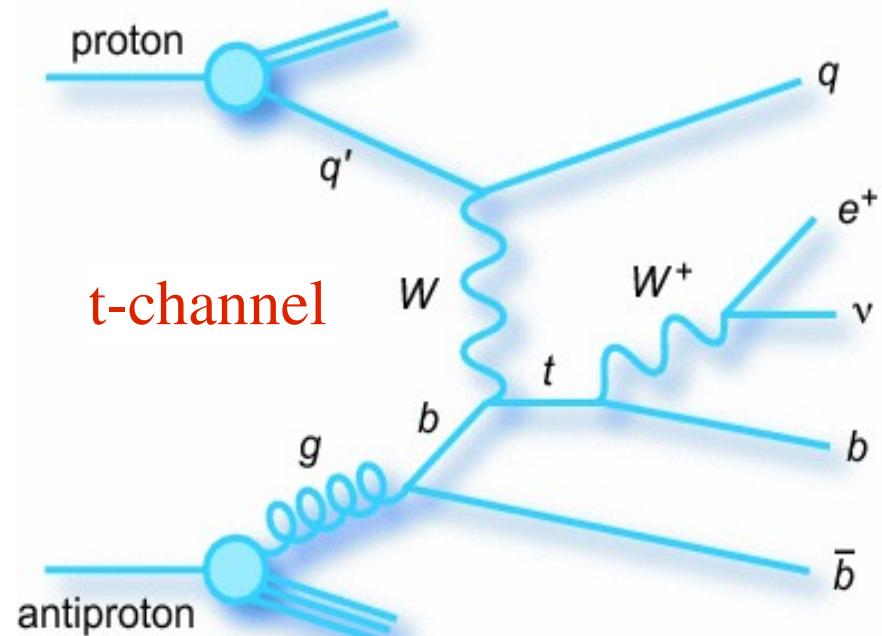
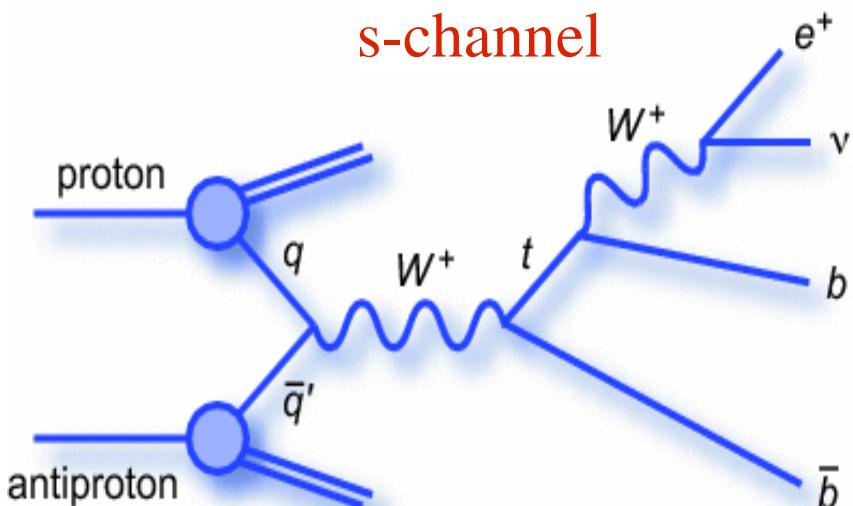




General analysis strategy

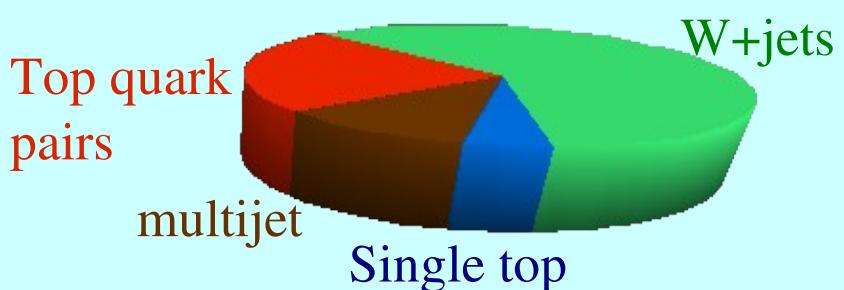


Event selection and sample composition



- One high- E_T lepton (electron or muon)
- Missing transverse energy MET (neutrino)
- ≥ 2 jets
 - s-channel: 2 b-quark jets
 - t-channel: 2 b-quark jets, and 1 light quark jet, q'

Event sample composition



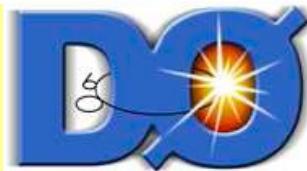


DO Results

[arXiv.org:0803.0739]

Supriya Jain, University of Oklahoma

Event yields



Source	Event Yields in 0.9 fb^{-1} Data		
	2 jets	3 jets	4 jets
$t b$	16 ± 3	8 ± 2	2 ± 1
tqb	20 ± 4	12 ± 3	4 ± 1
$t\bar{t} \rightarrow ll$	39 ± 9	32 ± 7	11 ± 3
$t\bar{t} \rightarrow l+jets$	20 ± 5	103 ± 25	143 ± 33
$W+b\bar{b}$	261 ± 55	120 ± 24	35 ± 7
$W+c\bar{c}$	151 ± 31	85 ± 17	23 ± 5
$W+jj$	119 ± 25	43 ± 9	12 ± 2
Multijets	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 41	460 ± 39	253 ± 38
Data	697	455	246

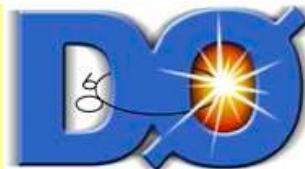
- Expected 62 single top events in 12 analysis channels

- Combined all channels as a product of Poisson likelihoods

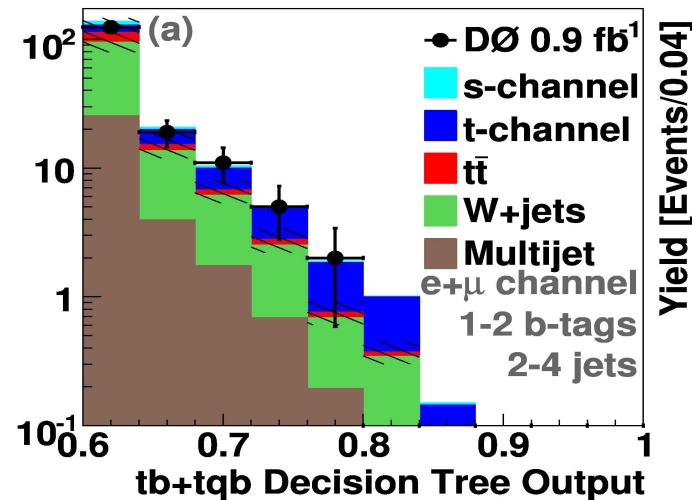
Percentage of single top $t b + tqb$ selected events and S:B ratio (white squares = no plans to analyze)

Electron + Muon	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
0 tags	10% 1 : 3,200	25% 1 : 390	12% 1 : 300	3% 1 : 270	1% 1 : 230
1 tag	6% 1 : 100	21% 1 : 20	11% 1 : 25	3% 1 : 40	1% 1 : 53
2 tags		3% 1 : 11	2% 1 : 15	1% 1 : 38	0% 1 : 43

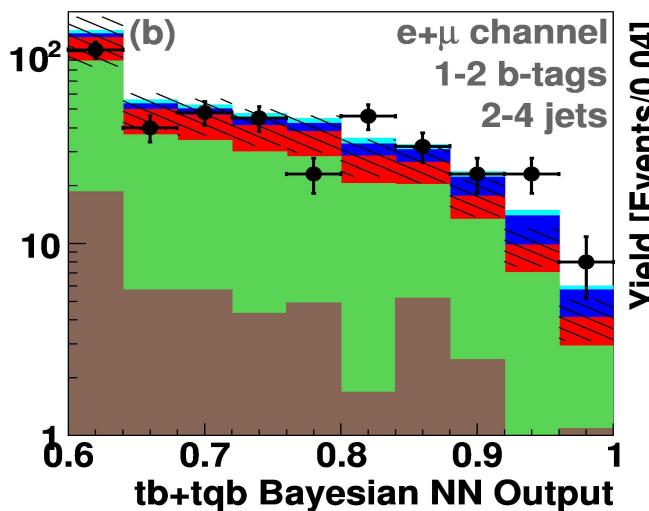
s+t cross section measurement (0.9 fb^{-1})



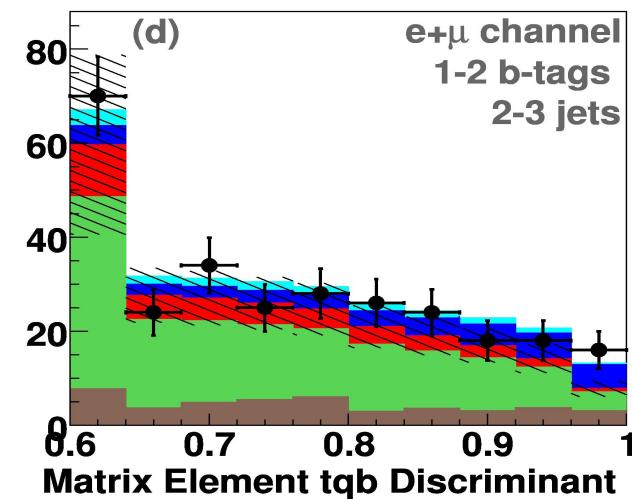
Boosted decision tree



Bayesian neural network



Matrix element method



- Measured σ_{s+t}

4.9 $^{+1.4}_{-1.4}$ pb

4.4 $^{+1.6}_{-1.4}$ pb

4.8 $^{+1.6}_{-1.4}$ pb

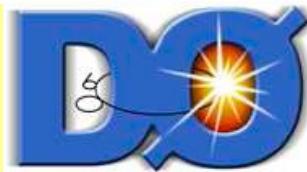
- Expected σ_{s+t}

2.7 $^{+1.6}_{-1.4}$ pb

2.7 $^{+1.5}_{-1.5}$ pb

2.8 $^{+1.6}_{-1.4}$ pb

D0 combination



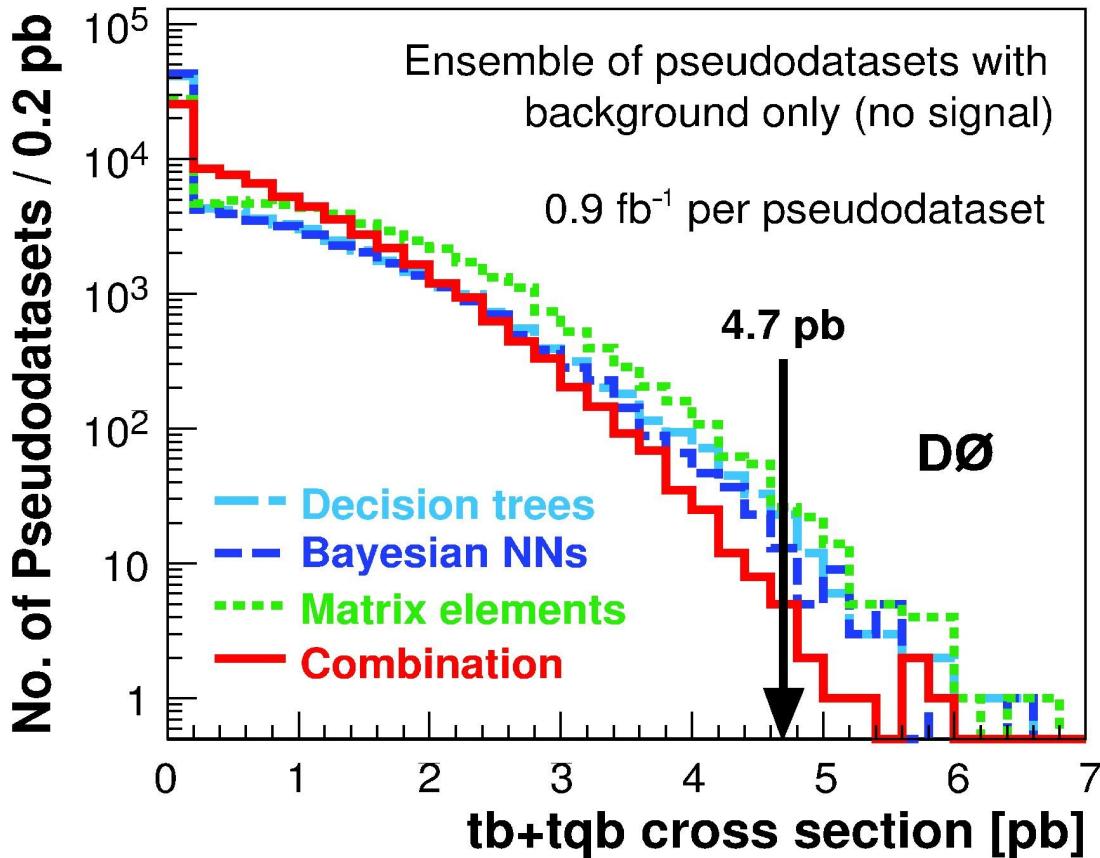
- Combine results using BLUE (best linear unbiased estimator) method
- Determine correlations from pseudo-datasets

- Measured σ_{s+t}
(Expected σ_{s+t})

$4.7^{+1.3}_{-1.3} \text{ pb}$

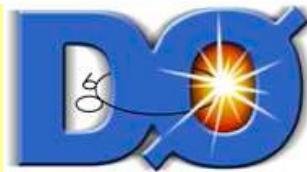
$(3.0^{+1.3}_{-1.3} \text{ pb})$

- Measured significance
[Expected significance]

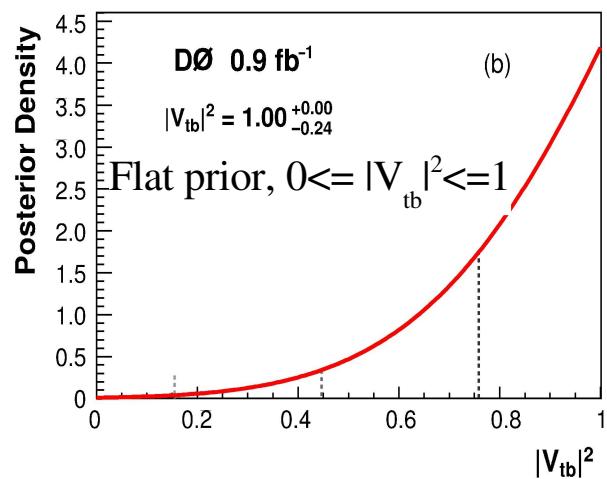
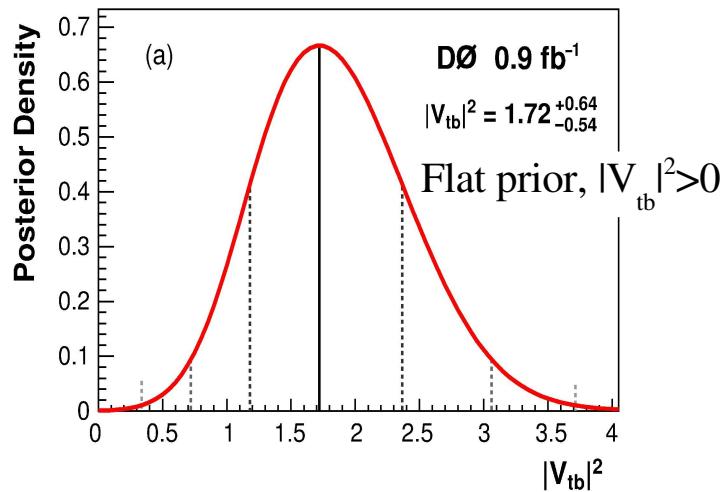


0.00014 (3.6 σ)
[0.011 (2.3 σ)]

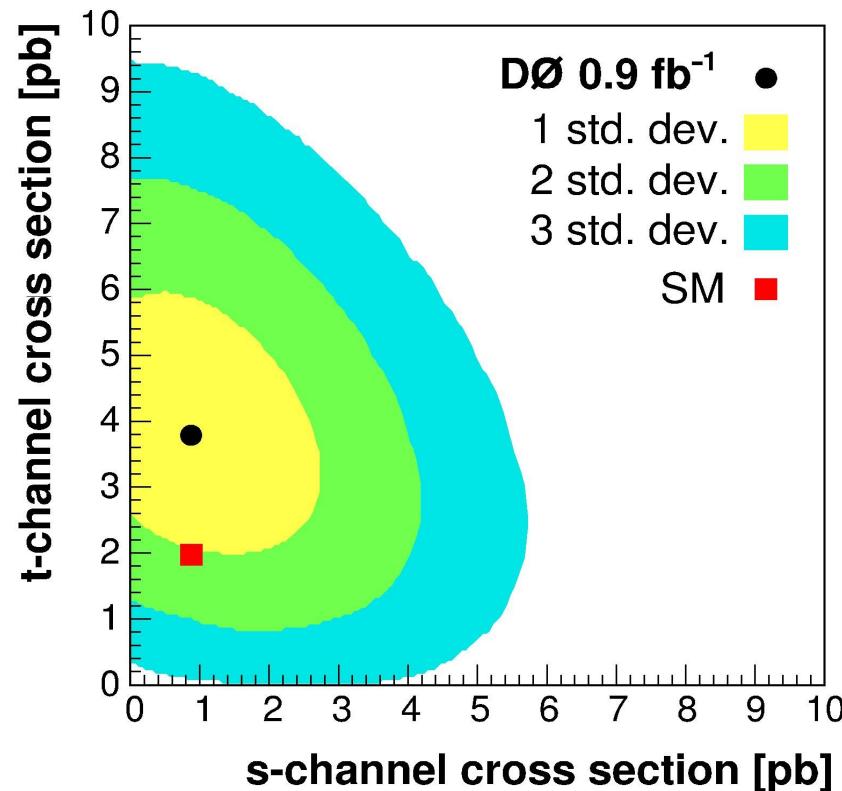
Other D0 measurements



- V_{tb}
- no constraint on unitarity, # of generations
- assuming $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$



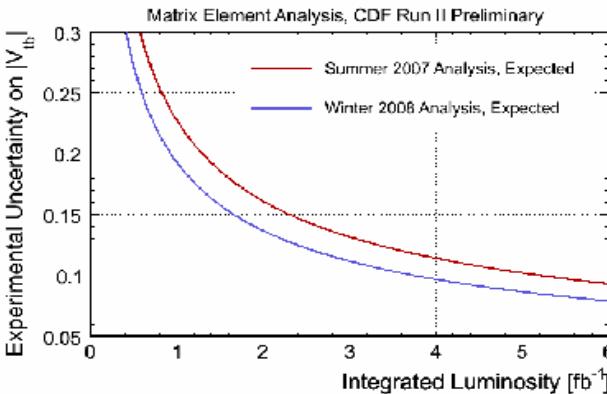
- Allowed contours at different levels of confidence in σ_s versus σ_t plane



CDF

Results

Expected uncertainty on $|V_{tb}|$ as a function of integrated luminosity.



The expected uncertainty is calculated assuming SM single top cross section. This plot is done with one of our analyses (matrix-element). The improvements in the new analysis translate in 15-20% in the expected sensitivity with respect to the old analysis.

CI

Tevatron Single Top Summary

Likelihood Function: CDF (2200 pb^{-1})	1.8 ± 0.8
Matrix Element: CDF (2200 pb^{-1})	2.2 ± 0.7
Neural Network: CDF (2200 pb^{-1})	2.0 ± 0.8
Decision Tree: D0 (500 pb^{-1})	4.9 ± 1.4
Matrix Element: D0 (500 pb^{-1})	4.8 ± 1.6
Neural Network: D0 (500 pb^{-1})	4.4 ± 1.4

SM Prediction

Single Top Production Cross Section (pb)

Color code :	< 1 fb^{-1}		1-1.9 fb^{-1}		> 1.9 fb^{-1}
Channel	Description (Link to web-page)		Measurement	Integrated Luminosity (pb^{-1})	Publication
Lepton+jets <i>New!</i>	Neural Network	s+t channel = $2.0 + 0.9 - 0.8 \text{ pb}$	2.2 fb^{-1}	02/27/2008 Conf. Note 9217	
Lepton+jets <i>New!</i>	Multivariate Likelihood Function	s+t channel = $1.8 + 0.9 - 0.8 \text{ pb}$ $ V_{tb} = 0.78 + 0.18 - 0.21(\text{exp}) +/ - 0.07(\text{theory})$	2.2 fb^{-1}	02/27/2008 Conf. Note 9221	
Lepton+jets <i>New!</i>	Matrix Element Discriminant	s+t channel = $2.2 + 0.8 - 0.7 \text{ pb}$ $ V_{tb} = 0.88 + 0.14 - 0.12(\text{exp}) +/ - 0.07(\text{theory})$	2.2 fb^{-1}	02/27/2008 Conf. Note 9223	
Lepton+jets	H_T	t-channel < 10.1 pb s-channel < 13.6 pb	160 pb^{-1}	01/28/2005 PRD 71 012005	
Lepton+jets <i>New!</i>	Search for $W \rightarrow tb$ using single top sample	$M_W > 800 \text{ GeV}/c^2$ for $M_W > M_{\nu_R}$ and $M_W > 825 \text{ GeV}/c^2$ for $M_W < M_{\nu_R}$ at 95% CL	1.9 fb^{-1}	12/20/2007 Conf. Note 9150	
				1 fb^{-1}	Conf. Note 8747

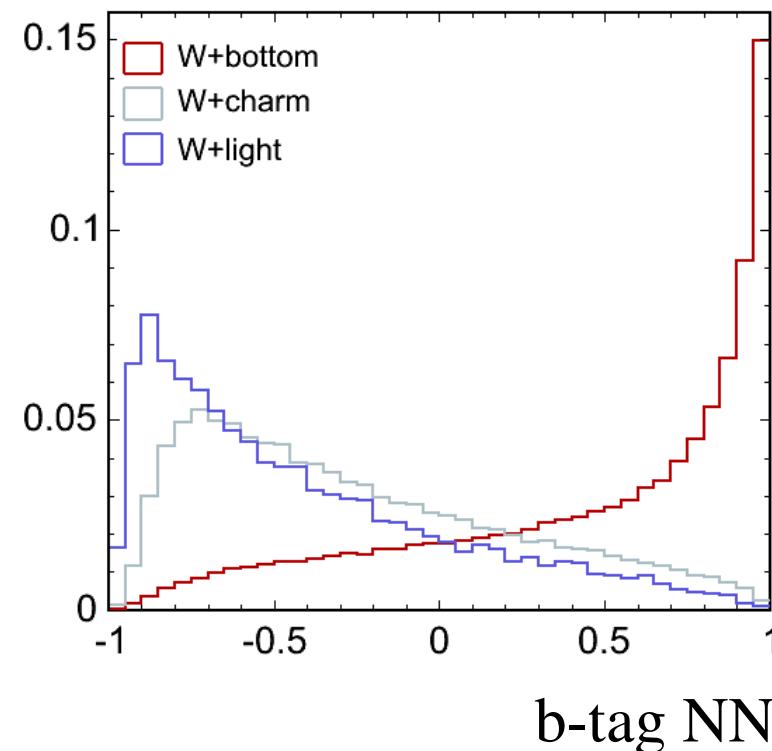
1.5 fb^{-1} to 2.2 fb^{-1}

- CDF confirmed evidence using 1.5 fb^{-1}
 - Measured (expected) significance: 3.1 (3.0) σ
- New results using 2.2 fb^{-1}
 - Increased acceptance
 - extended muon coverage by adding new triggers
 - included 3-jet channel (besides 2-jet channel)
 - Improved performance of multivariate techniques

Process	CDF Run II Preliminary Predicted event yield with 2.2 fb^{-1}	
	2 jets	3 jets
s-channel	41.2 \pm 5.9	13.5 \pm 1.9
t-channel	62.1 \pm 9.1	18.3 \pm 2.7
Single top	103.3 \pm 15.0	21.8 \pm 4.6
$t\bar{t}$	146.0 \pm 20.9	338.7 \pm 48.2
Diboson	63.2 \pm 6.3	21.5 \pm 2.2
Z + jets	26.7 \pm 3.9	11.0 \pm 1.6
W + bottom	461.6 \pm 139.1	141.1 \pm 42.6
W + charm	395.0 \pm 121.8	108.8 \pm 33.5
W + light	339.8 \pm 56.1	101.8 \pm 16.9
Multijet	59.5 \pm 23.8	21.3 \pm 8.5
Total background	1491.8 \pm 268.6	754.8 \pm 91.3
Total prediction	1595.1 \pm 269.0	776.6 \pm 91.4
Observed	1535	712

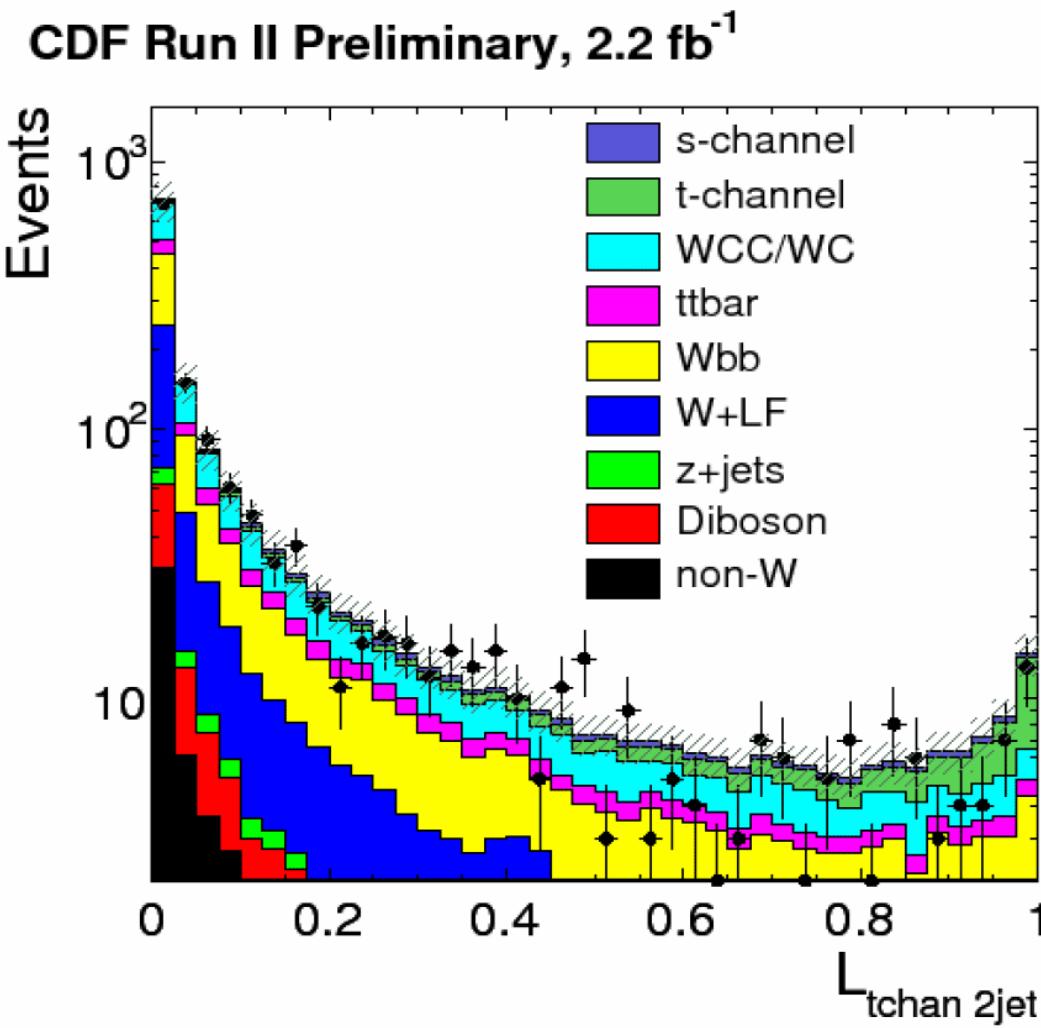
Likelihood method

- Likelihood functions built from several variables
 - Kinematic variables, b-tag NN, t-channel ME, kinematic solver



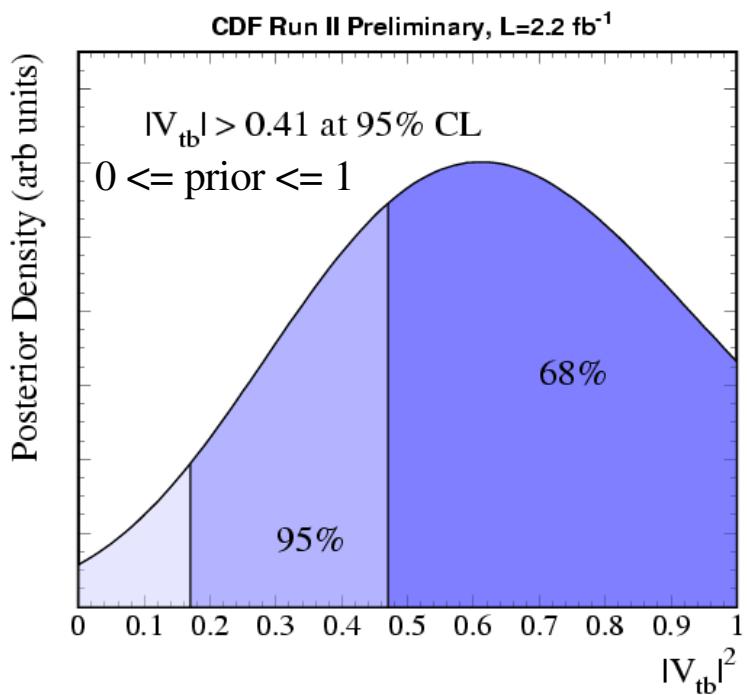
Likelihood method

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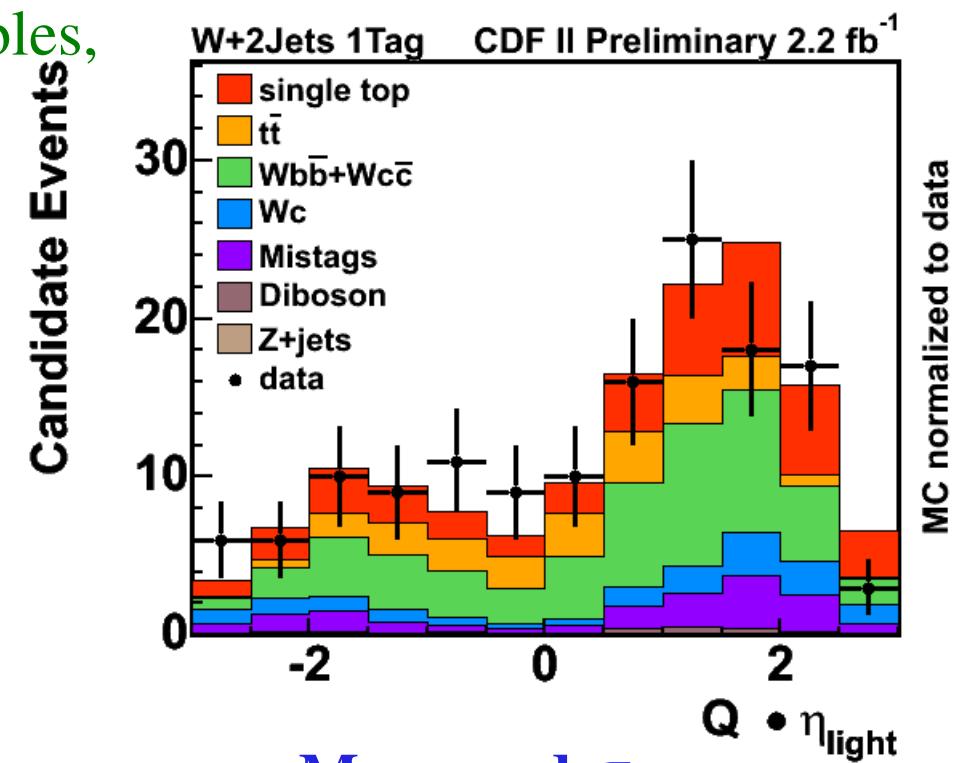
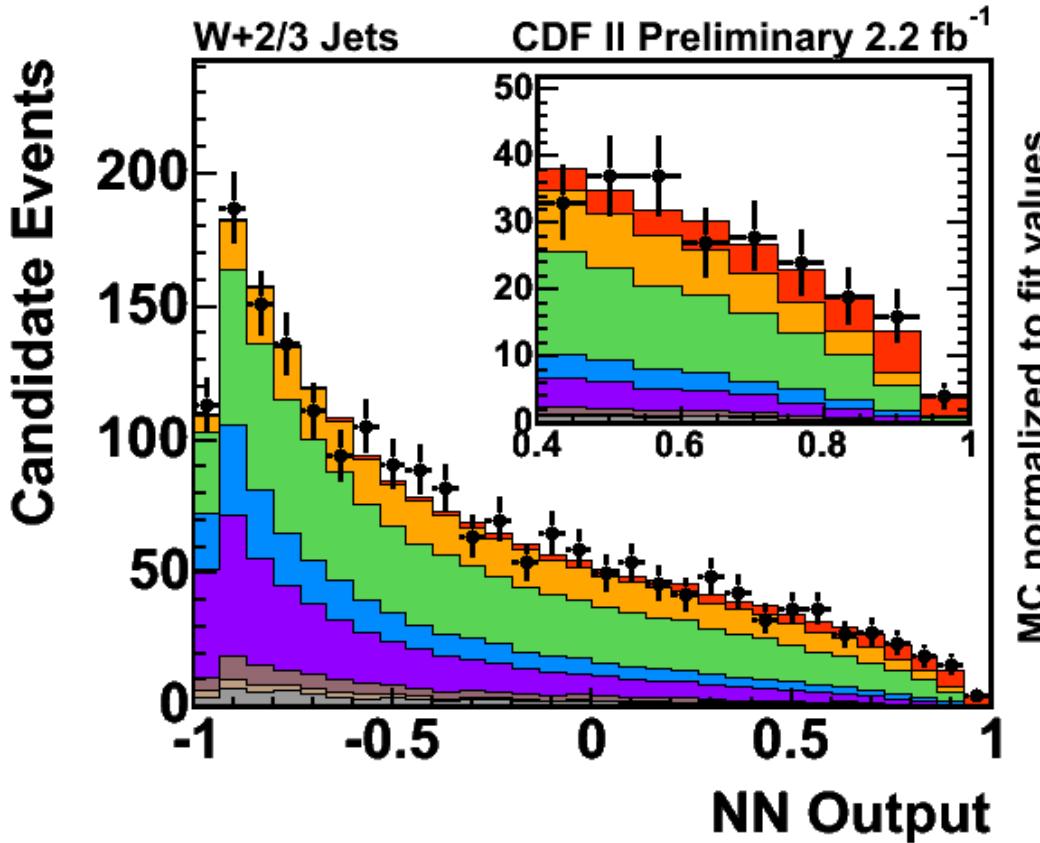
- Measured σ_{s+t}

$1.8^{+0.9}_{-0.8} \text{ pb}$



Neural networks

- 4 separate networks built in 2jet-1tag, 2jet-2tag, 3jet-1tag, and 3jet-2tag channels
 - Train for t-channel in 1-tag events, and s-channel in 2-tag events
 - Including b-tag NN, kinematic variables, angular correlations

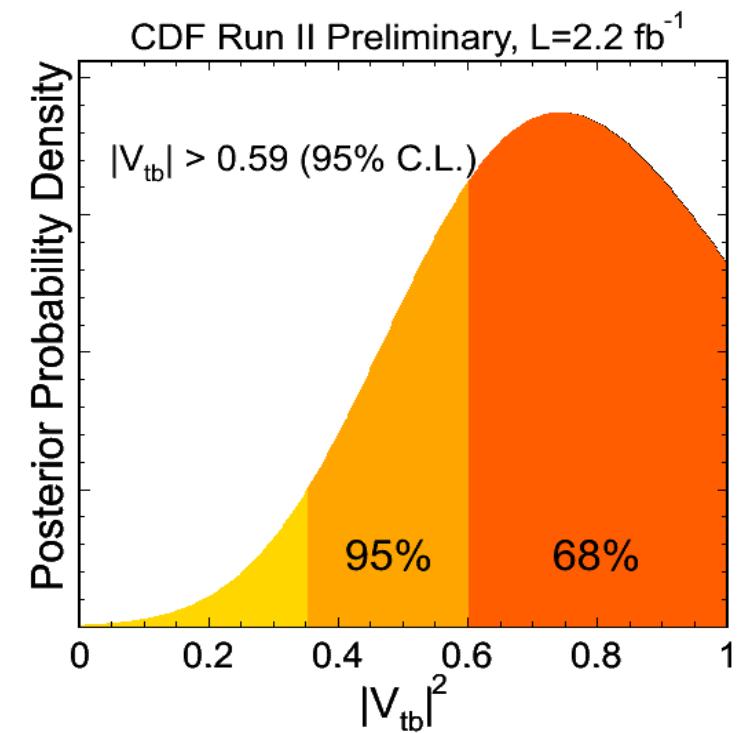
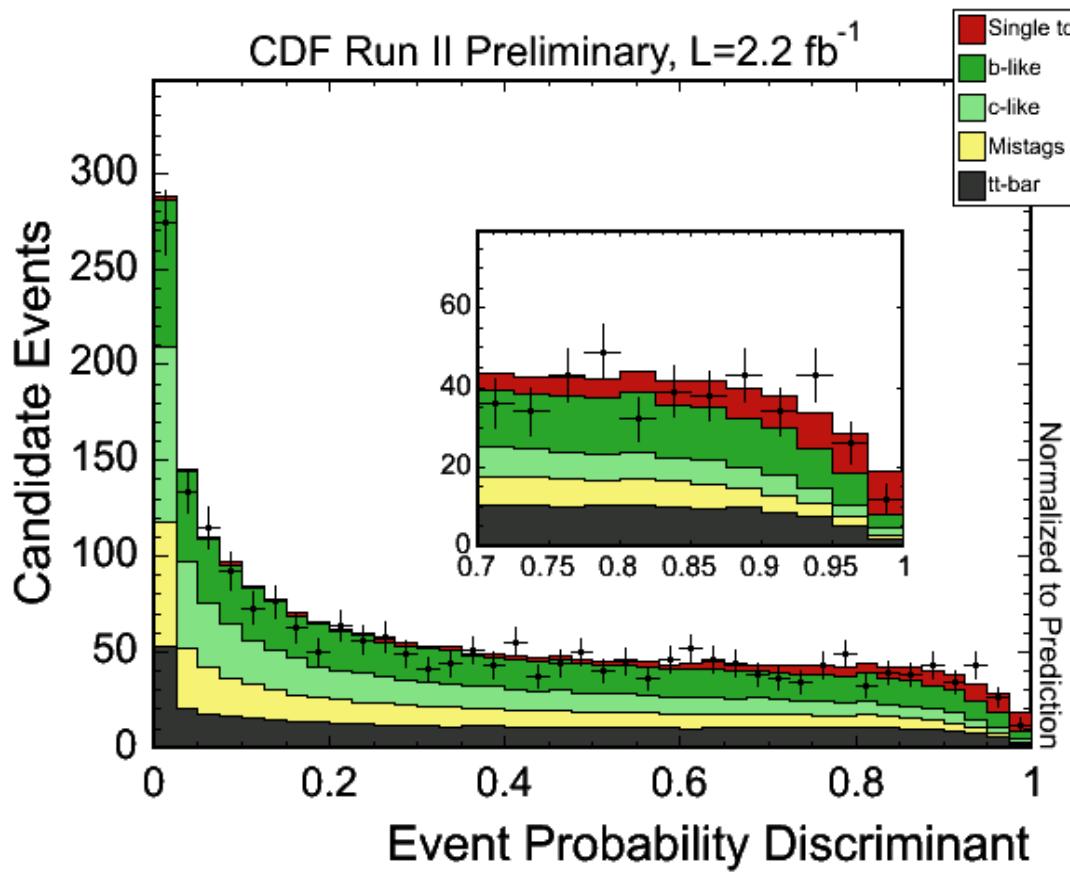


- Measured σ_{s+t}

$2.0^{+0.9}_{-0.8} \text{ pb}$

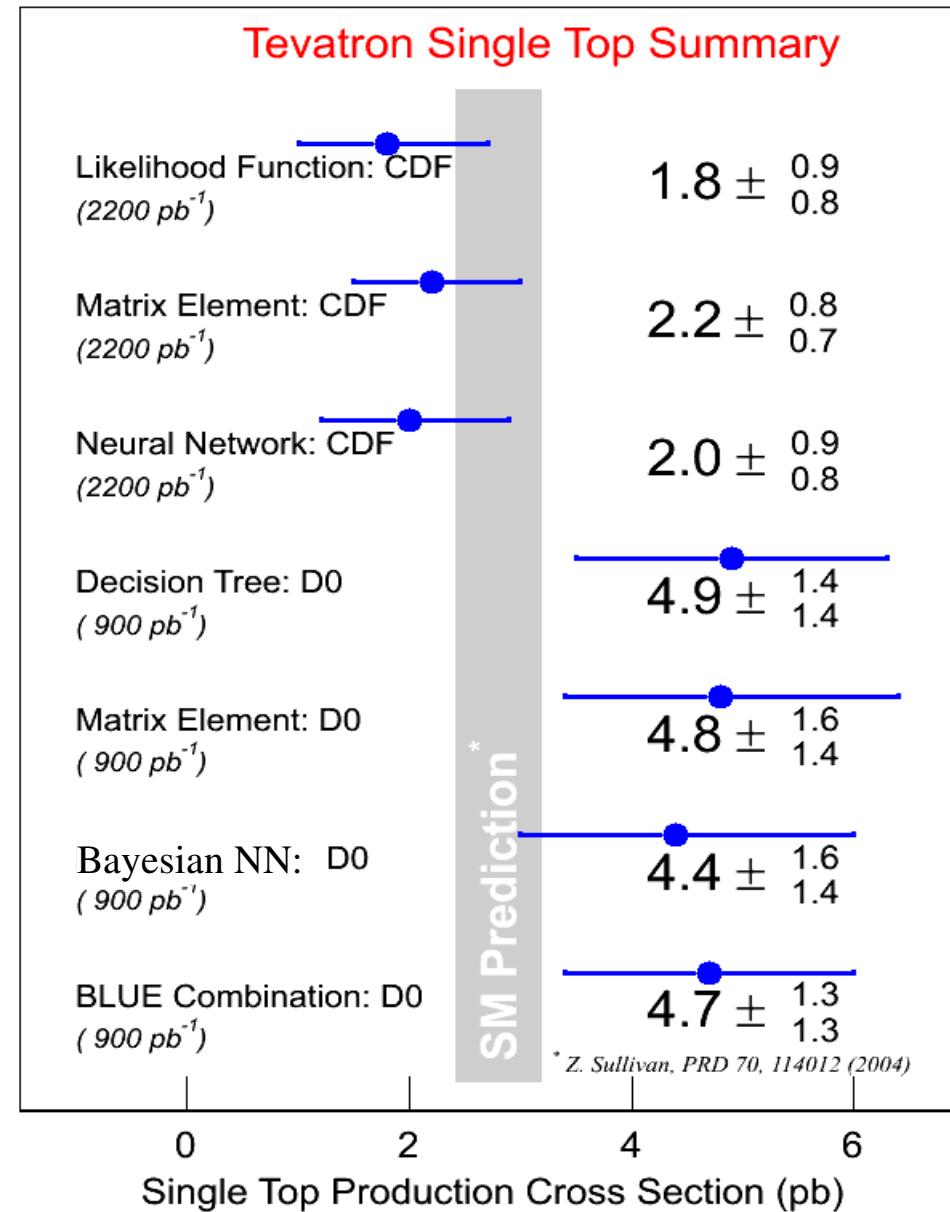
Matrix element

- Include ttbar matrix element for both 2-jet and 3-jet events
- Include b-tag NN as weight in likelihood ratio

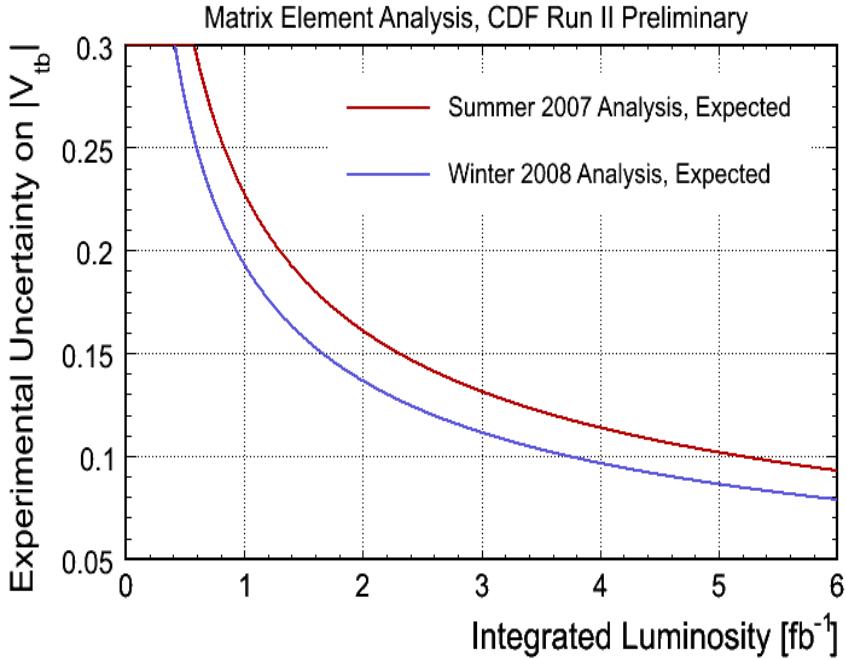


- Measured σ_{s+t}

$2.2^{+0.8}_{-0.7} \text{ pb}$

Tevatron summary (σ_{s+t})

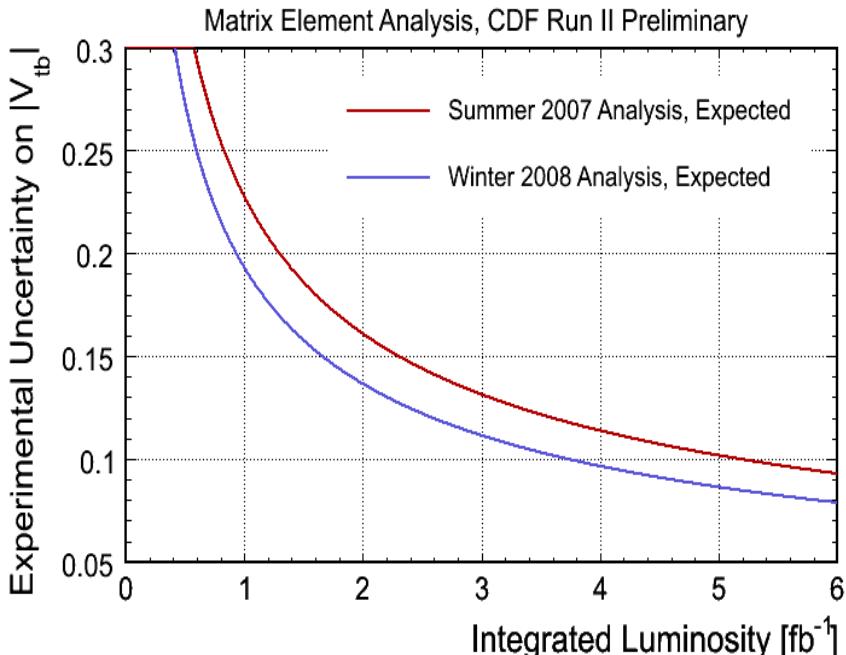
Tevatron projections



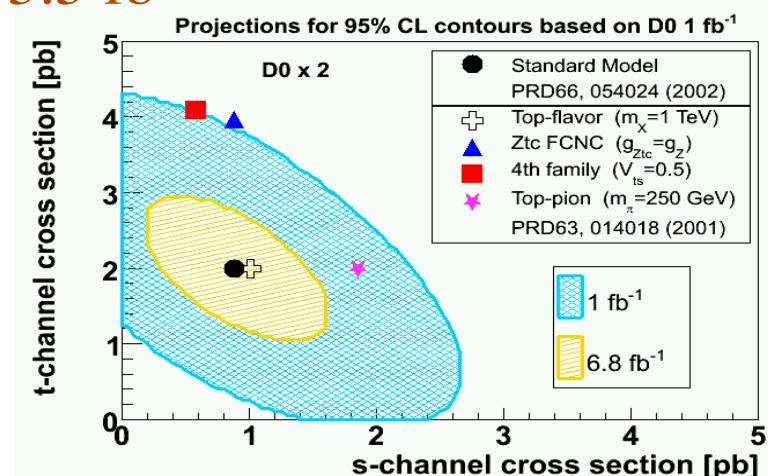
- Based on current measurement, CDF predicts 10% precision on $|V_{tb}|$ measurement at 3.5 fb^{-1}



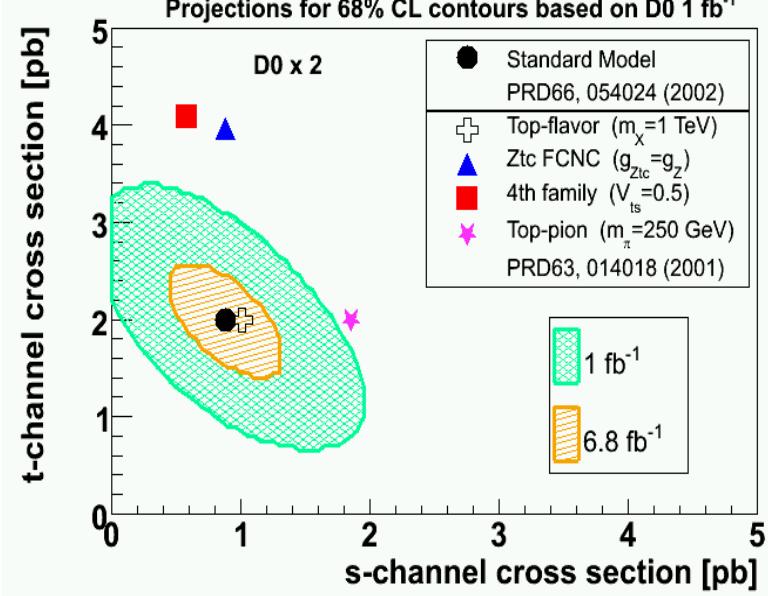
Tevatron projections



- Based on current measurement, CDF predicts 10% precision on $|V_{tb}|$ measurement at 3.5 fb^{-1}

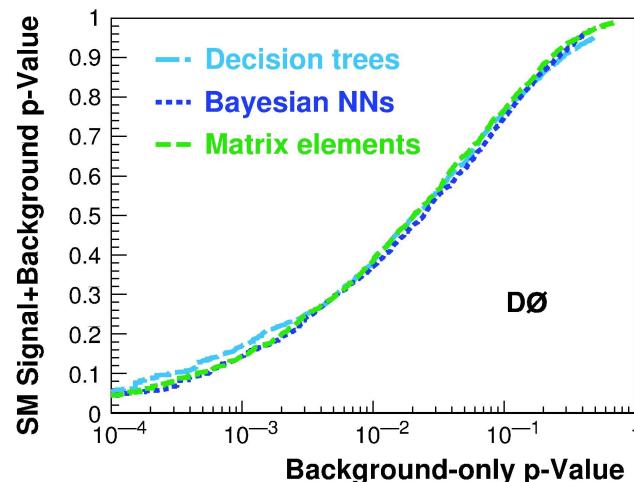


- Based on the Bayesian NN analysis, D0 predicts the following contours in σ_s versus σ_t plane at 95% CL and 68% CL with twice its data at 7 fb^{-1}



Conclusions

- The search for single top quark production is turning into measurements in the single top final state
 - Both experiments have seen 3σ evidence
 - First direct measurement of $|V_{tb}|$ performed
- Further improvements in progress
 - CDF combination
 - DØ update with larger dataset
- Several multivariate techniques, some new to our field, have been explored
 - Show similar performance in DØ analyses

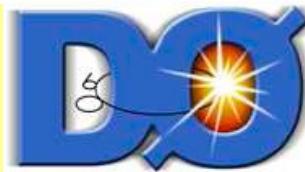




Backup slides



Systematics



CDF Run II Preliminary

Systematic uncertainty	Range of Effect	Shape variations
Jet energy scale	0...16%	✓
Initial state radiation	0...11%	✓
Final state radiation	0...15%	✓
Parton distribution functions	2...3%	✓
Monte Carlo generator	1...5%	
Event detection efficiency	0...9%	
Luminosity	6%	
Neural net jet flavor separator		✓
Mistag model		✓
Non-W model		✓
Q^2 scale in Alpgen Monte Carlo		✓
Monte Carlo mismodeling		✓

D0

TABLE XI: Summary of the relative systematic uncertainties. The ranges shown represent the different samples and channels.

Relative Systematic Uncertainties	
Integrated luminosity	6%
$t\bar{t}$ cross section	18%
Electron trigger	3%
Muon trigger	6%
Primary vertex	3%
Electron reconstruction & identification	2%
Electron track match & likelihood	5%
Muon reconstruction & identification	7%
Muon track match & isolation	2%
Jet fragmentation	(5–7)%
Jet reconstruction and identification	2%
Jet energy scale	(1–20)%
Tag-rate functions	(2–16)%
Matrix-method normalization	(17–28)%
Heavy flavor ratio	30%
$\varepsilon_{\text{real-}e}$	2%
$\varepsilon_{\text{real-}\mu}$	2%
$\varepsilon_{\text{fake-}e}$	(3–40)%
$\varepsilon_{\text{fake-}\mu}$	(2–15)%

Some b-tagging details (D0)

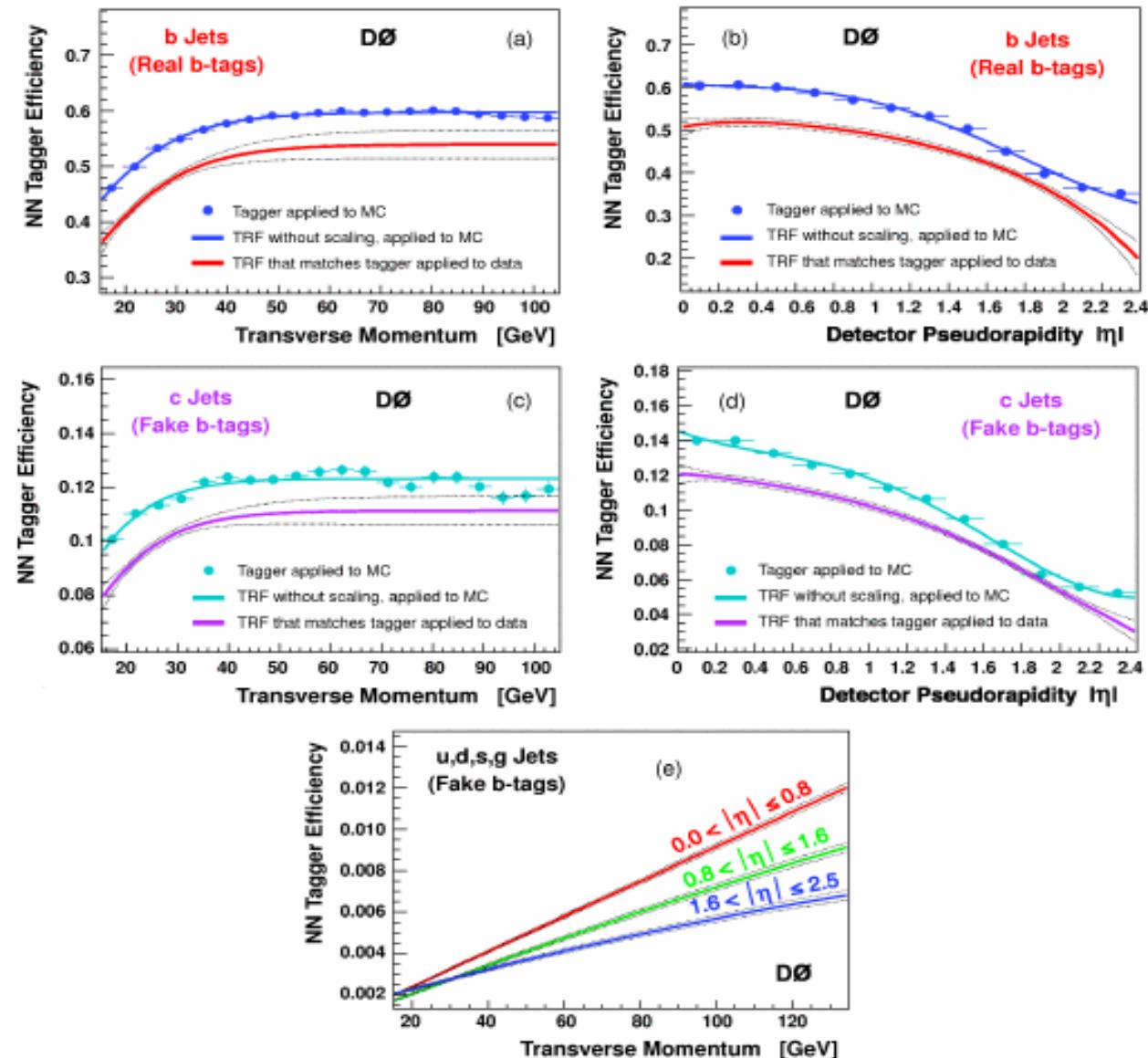


FIG. 3: The tag-rate functions (TRFs) used to weight the MC events according to the probability that they should be b tagged. In plots (a)–(d), the points show the neural network b tagging algorithm (the “tagger”) applied directly to the MC events. The upper line that passes through the points is the result of the tag-rate functions, before scaling-to-data, being applied to the MC events to reproduce the result from the tagger. The lower line, with dotted error band, shows the tag-rate functions after they have been scaled to match the efficiency of the NN b tagging algorithm applied to data. In plot (e), the lines show the (scaled) tag-rate functions that are applied to MC events.

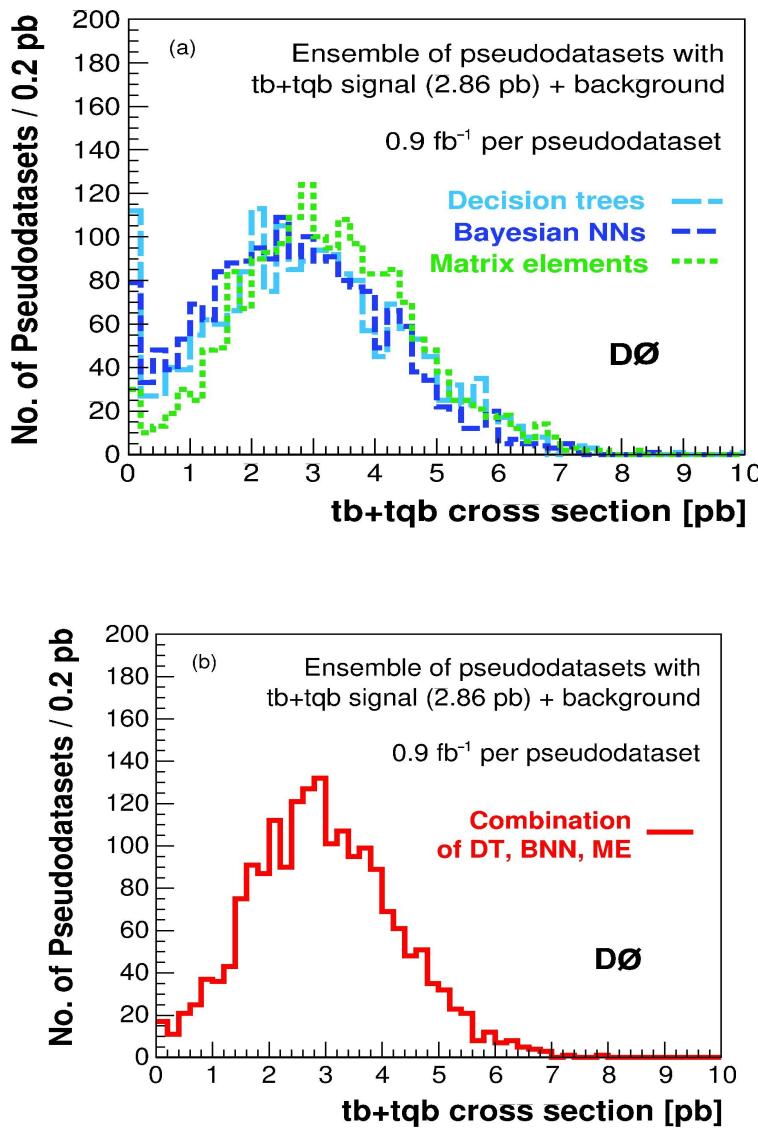


TABLE I: Mean and square root of variance from the SM signal (2.9 pb) + background ensembles for the different analyses.

Analysis	Mean	$\sqrt{\text{Var}}$	$\sigma/\Delta\sigma$
	σ [pb]	$\Delta\sigma$ [pb]	
Decision trees (DT)	2.9	1.61	1.8
Matrix elements (ME)	3.2	1.42	2.3
Bayesian neural networks (BNN)	2.7	1.48	1.8
Combined	3.0	1.28	2.3

$$\rho = \begin{pmatrix} DT & ME & BNN \\ 1 & 0.64 & 0.66 & DT \\ 0.64 & 1 & 0.59 & ME \\ 0.66 & 0.59 & 1 & BNN \end{pmatrix}$$

TABLE II: The expected p -values and significances for the individual and the combined analyses, using the SM value of 2.9 pb for signal cross section as the reference point in Fig. 3.

Analysis	Expected p -value	Expected significance [std. dev.]
Decision trees (DT)	0.0177	2.1
Matrix elements (ME)	0.0307	1.9
Bayesian neural networks (BNN)	0.0155	2.2
Combined	0.0105	2.3

- Calculate probability density of an event resulting from a given process

Integrate over parton-level quantities

Parton distribution functions

$$P(p_i^\mu, p_{j1}^\mu, p_{j2}^\mu) = \frac{1}{\sigma} \int d\rho_{j1} d\rho_{j2} dp_t^z \sum_{\text{combi}} \phi_4 |M(p_i^\mu)|^2 \frac{f(q_1)f(q_2)}{|q_1| |q_2|} W_{jet}(E_{jet}, E_{part})$$

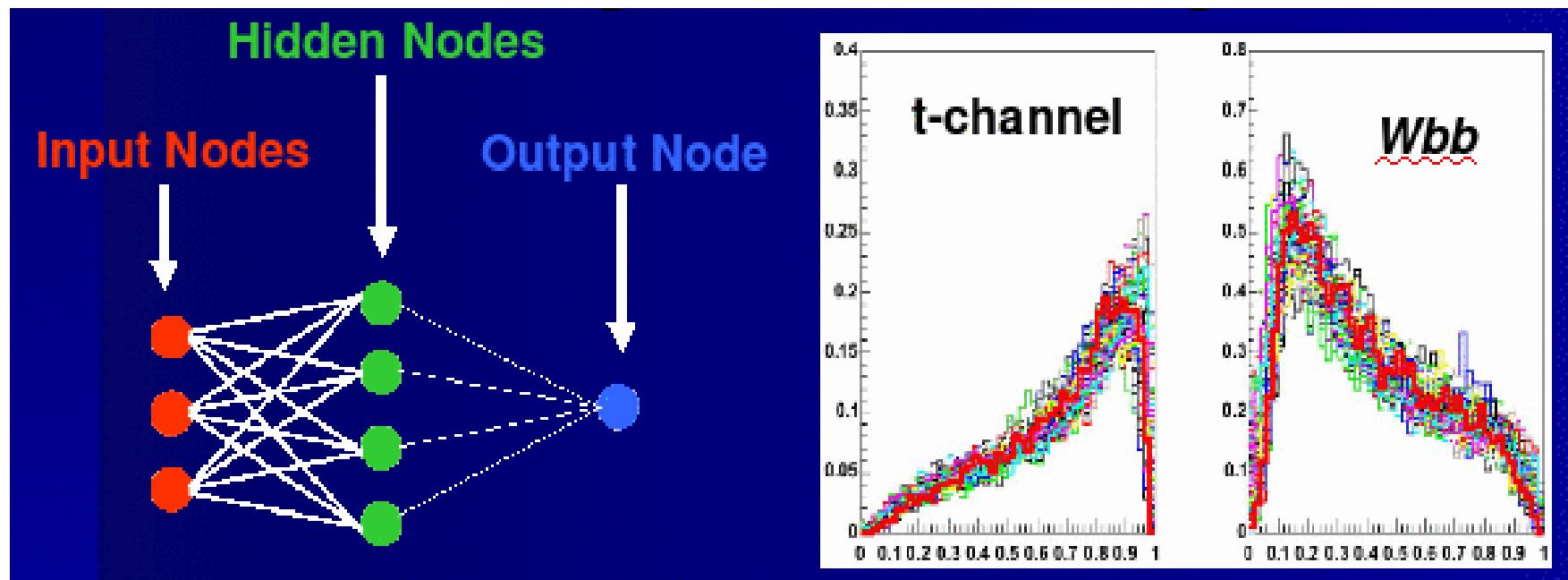
Inputs:
lepton and jet 4-vectors
– no other information needed!

Matrix element:
Different for each process.
Leading order, obtained from MadGraph

Transfer functions:
Account for detector effects in measurement of jet energy

- Uses full kinematic information of an event to discriminate signal events from background events
- Calculate probabilities for s- and t-channel, Wbb , Wcj , Wgg , and $t\bar{t}$ -bar (for three-jet events)
- Use matrix element probability densities to create a discriminant: signal / (signal + background)

- Neural networks are trained on Monte Carlo to discriminate signal from background
- A Bayesian neural network is a weighted average of many networks
- Protected against overtraining



- Start with large number of input variables (49)
- Optimize series of binary cuts in Monte Carlo
 - Automatically finds “interesting” variables
- Sort events by output purity
- Create series of “boosted” trees by reweighting based on misclassified events

